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High Power Lasers – Systems & Weapons

by

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Folkestone, Kent – 11th April 2017, 10.30 am

Summary

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- Some laser history
- Airborne Laser Testbed & COIL
- Laser modes and beam propagation
- Fibre lasers and applications
- US Navy Laser system – NRL 33kW fibre laser
- Lockheed Martin 30kW now 60kW fibre laser
- UK activity
- Textron are offering 150kW beam weapons
- Conclusions

Brief History and Evolution of Lasers

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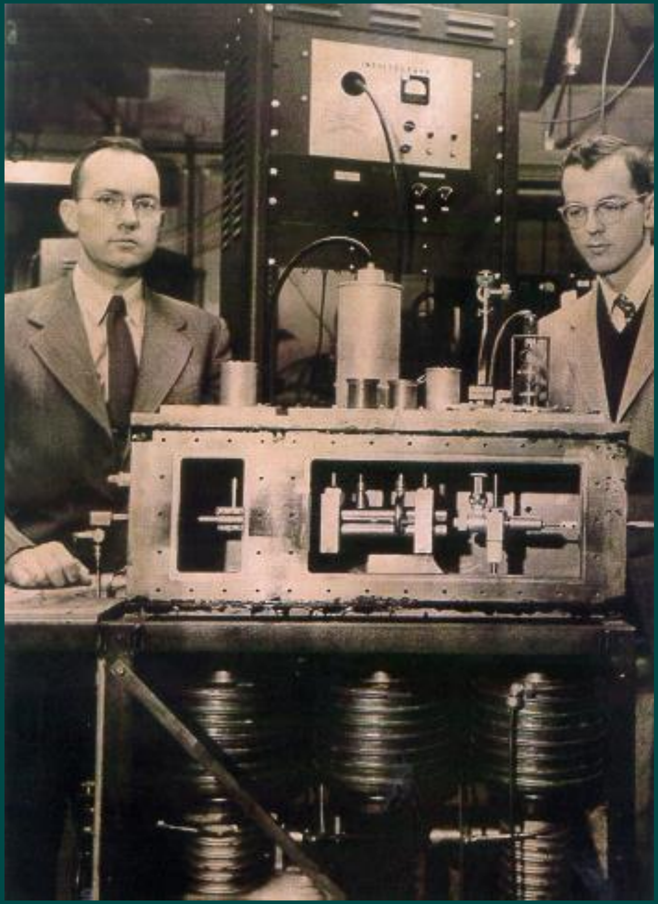
- 1917 - Albert Einstein developed the concept of stimulated emission, which is the phenomenon used in lasers
- In 1954 the MASER was the first device to use stimulated emission (Townes & Schawlow). Microwave amplification by stimulated emission of radiation

Brief History of Lasers



Charles Townes & Jim Gordon at Columbia University in 1954 with their second working MASER

- In 1958 Townes & Schawlow suggested that stimulated emission could be used in the infrared and optical portions of the spectrum
- The device was originally termed the optical maser
- This term was dropped in favour of LASER. Standing for Light Amplification by Stimulated Emission of Radiation

1st Laser - Ted Maiman 15th May 1960

- working alone and against the wishes of his boss at Hughes Research Laboratories

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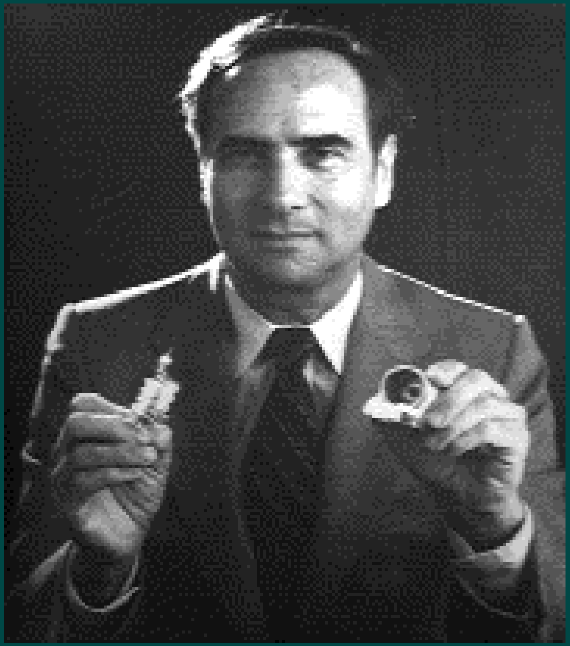
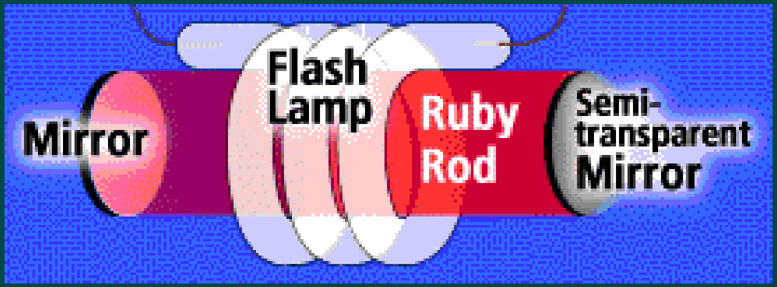


Electrical Engineer

Original Laboratory
Set-Up for the Ruby Laser



Maiman's Ruby Laser - 694.3 nm

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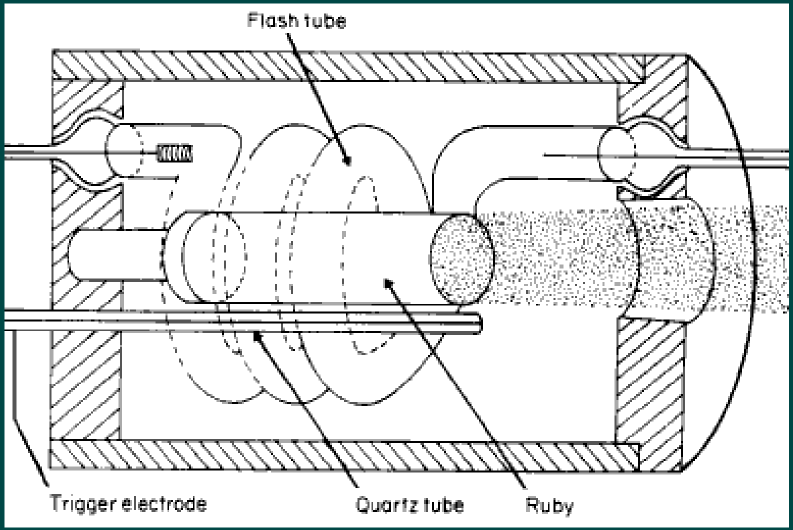
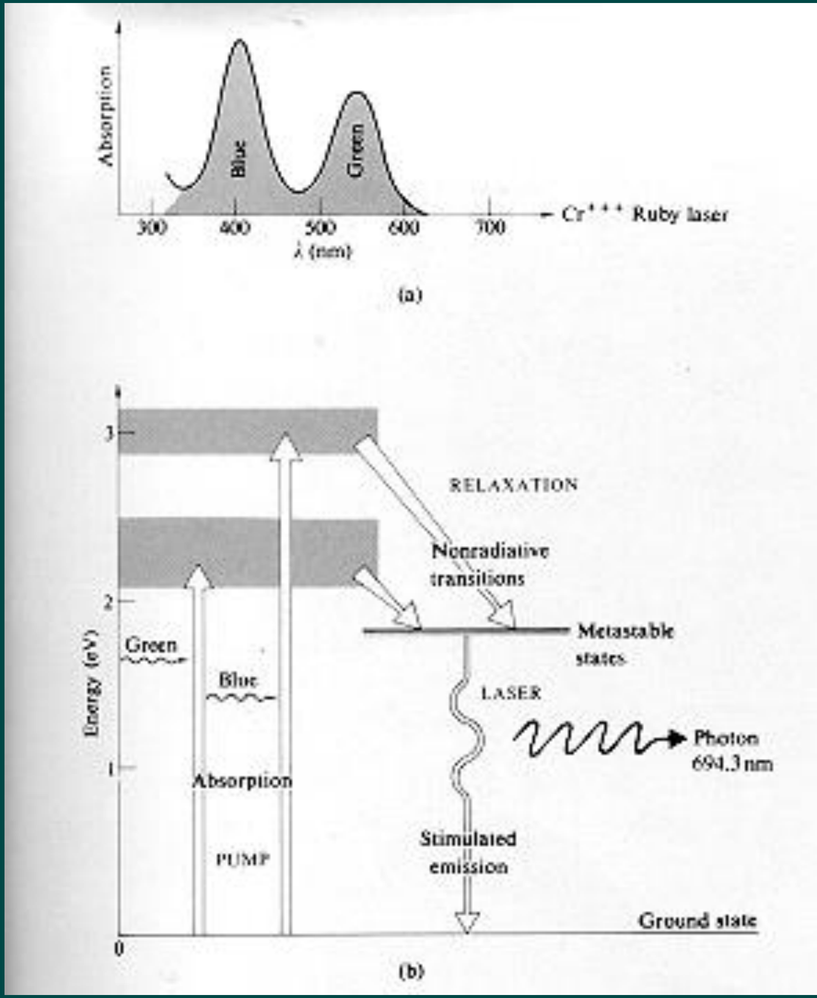
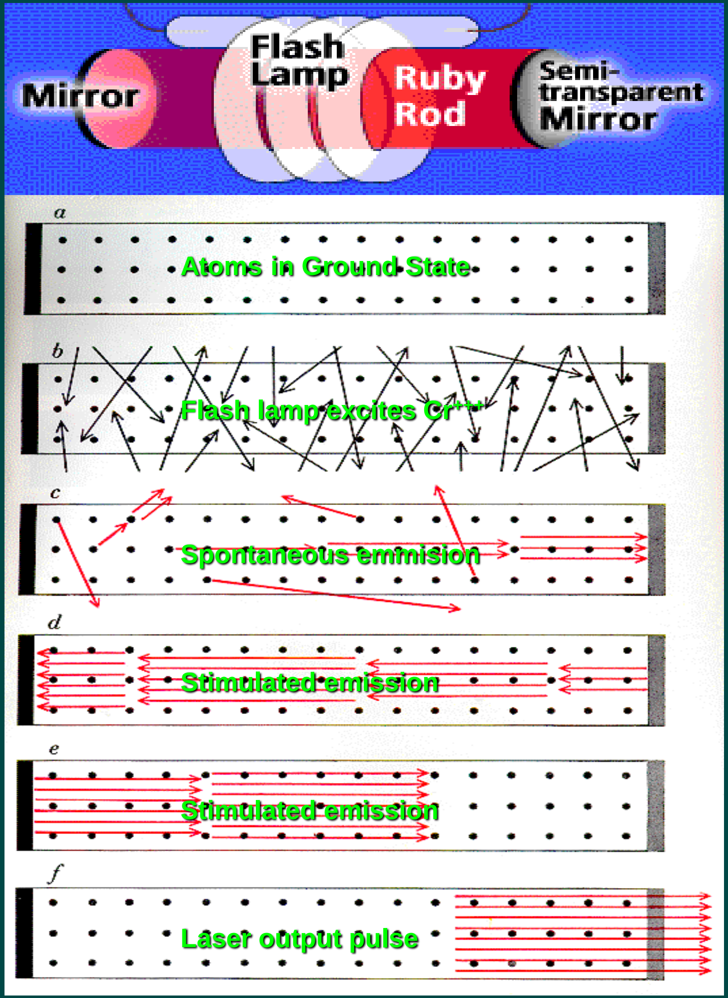


New York Times
8th July 1960,
Wrong Ruby Crystal
is shown here.
The journalist didn't
like the actual stubby
crystal. This crystal
was used later

Synthetic pale pink ruby crystal Al_2O_3
containing about 0.05% by weight of Cr_2O_3

Stimulated Emission





Coherence and Focusing

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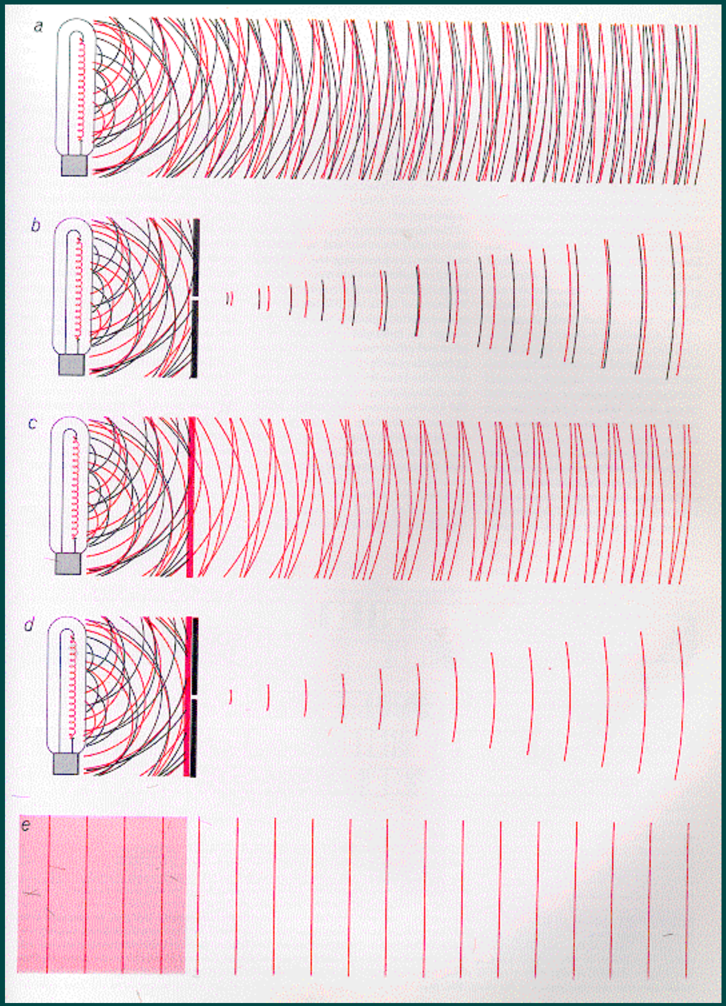


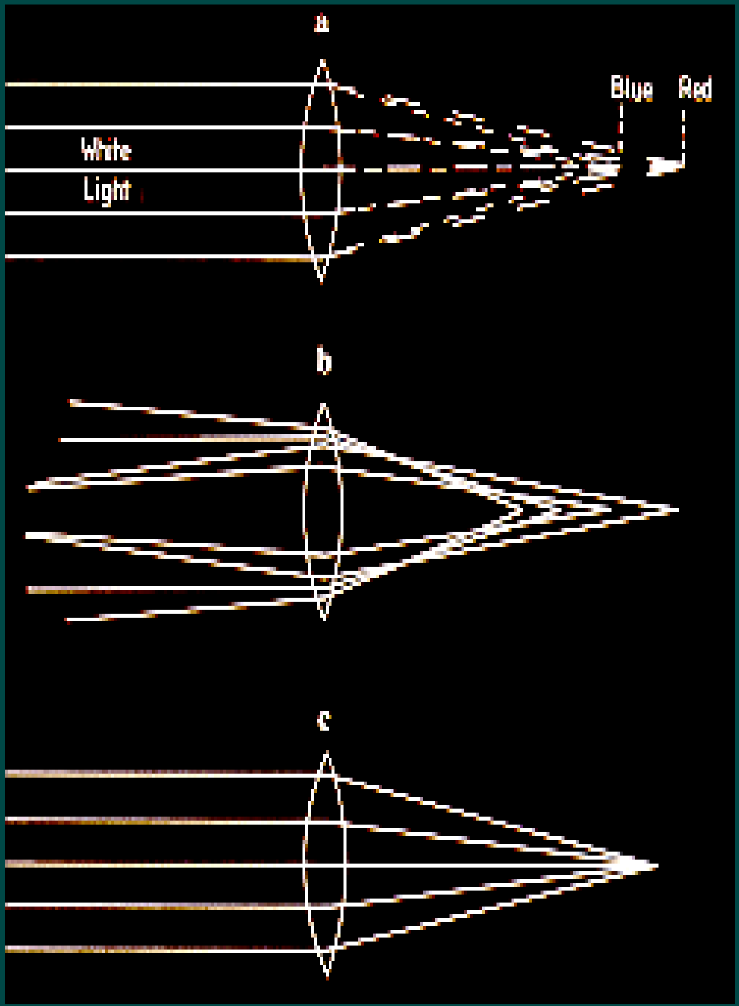
Spatially & temporally incoherent:out-of-step & various wavelengths

Spatially Coherent

Temporally coherent single wavelength

Spatially & temporally coherent- only 1% left

Laser Light
100% coherent



A Beam Focusing Lens and an Assist Gas Nozzle is required for all but UV lasers

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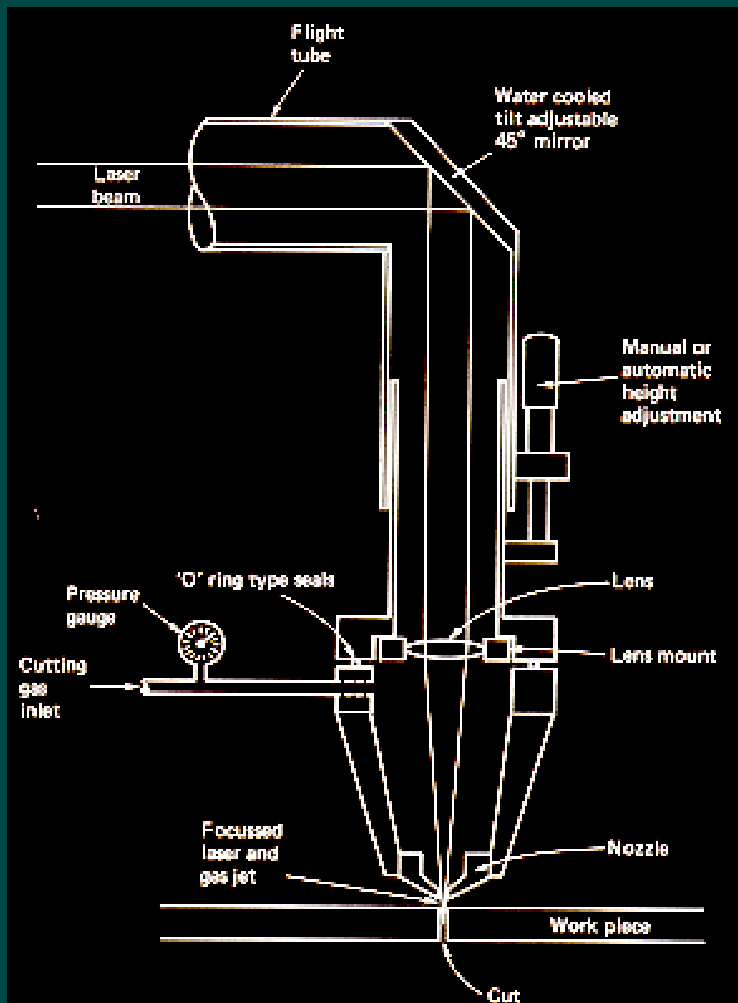
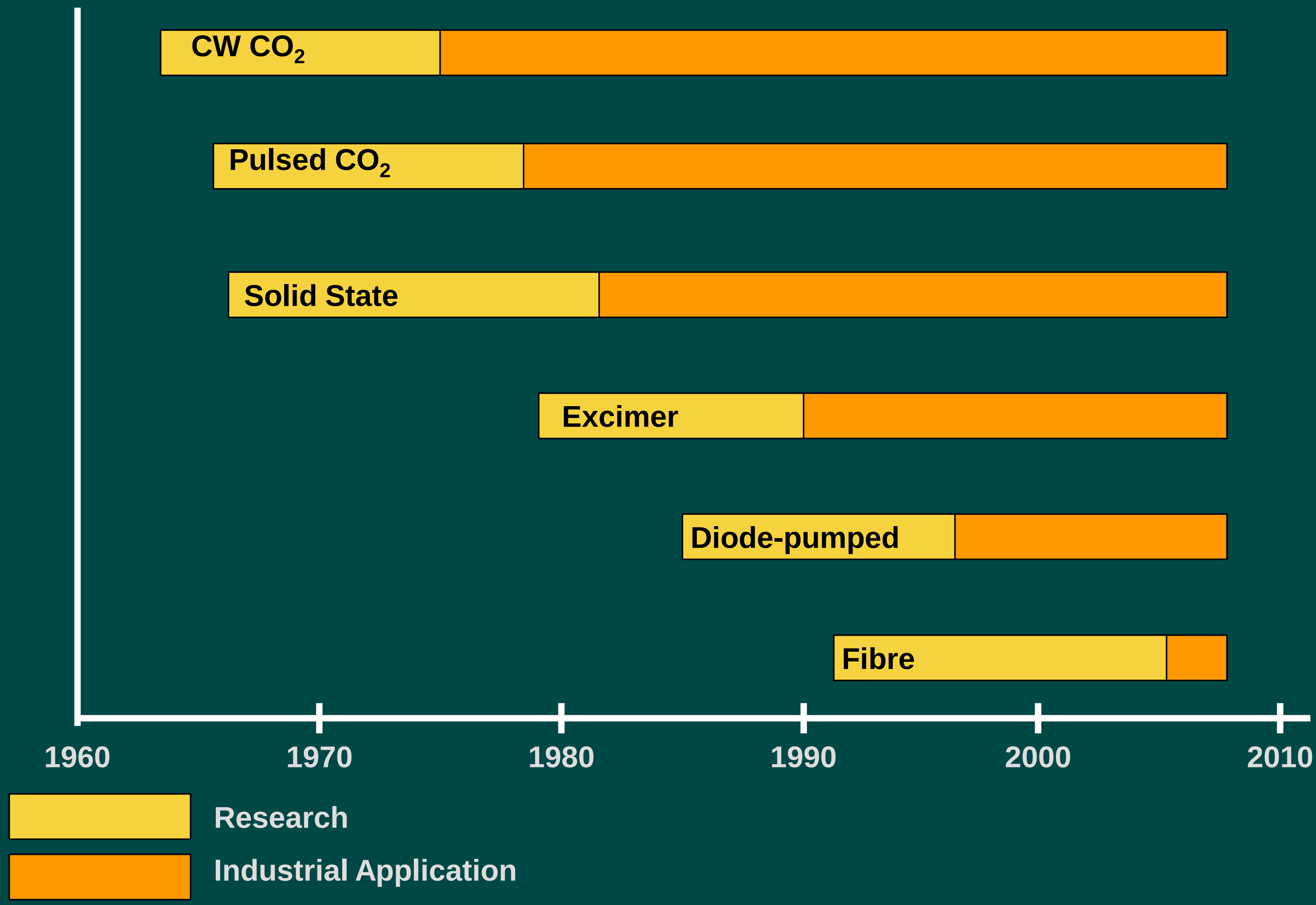


Gases: Oxygen, Nitrogen, Argon, Helium etc.

http://www.youtube.com/watch?v=uuLAkC6jrP0 laser cutting

Evolution of Industrial Lasers



High Power Materials Processing Lasers

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- Carbon Dioxide - up to 100kW more usually 2 to 7kW - 10.6μm[14,16]
- Nd-YAG - up to 4.5kW - 1.06μm - diode pumped[17]
- Diode Lasers 2 kW
- Fibre Lasers 10kW single mode 50kW multimode >25% efficiency 1.064μm
- Chemical oxygen iodine laser, or COIL, is an infrared chemical laser – wavelength 1.315 μm, a transition wavelength of atomic iodine

The Boeing YAL-1 Airborne Laser Testbed (ALTB)

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- The **Boeing YAL-1** Airborne Laser Testbed weapons system was a megawatt-class chemical oxygen iodine laser (COIL) mounted inside a modified Boeing 747-400F.
- It is primarily designed as a missile defense system to destroy tactical ballistic missiles (TBMs), while in boost phase.
- Contractors: Boeing Defence (Aircraft), Northrop Grumman (COIL), Lockheed Martin (Nose turret and fire control system)

Megawatt Airborne Laser Test Bed (ALTB)

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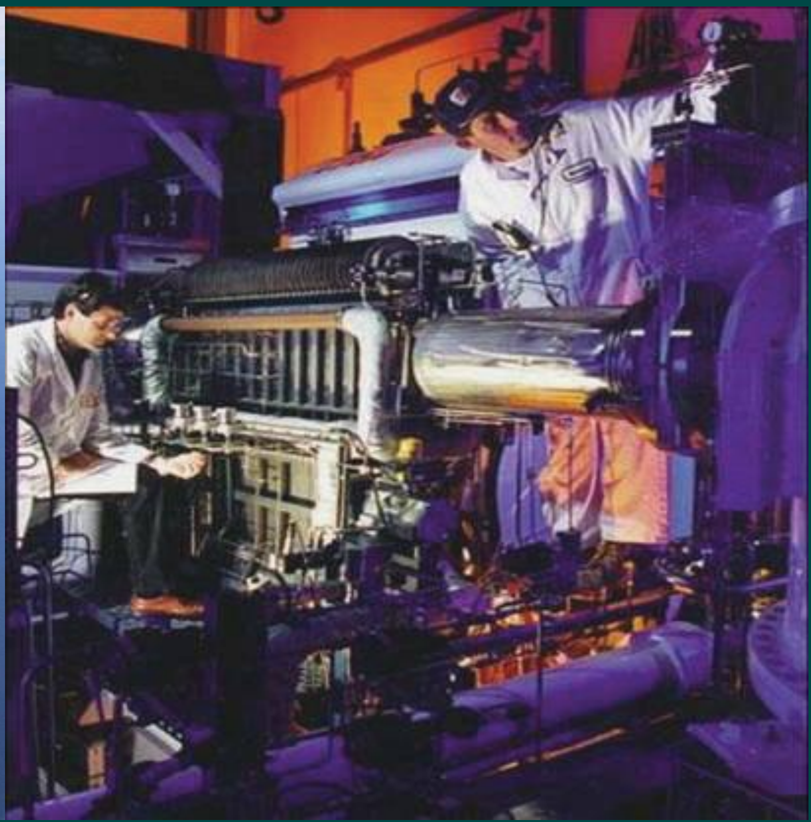
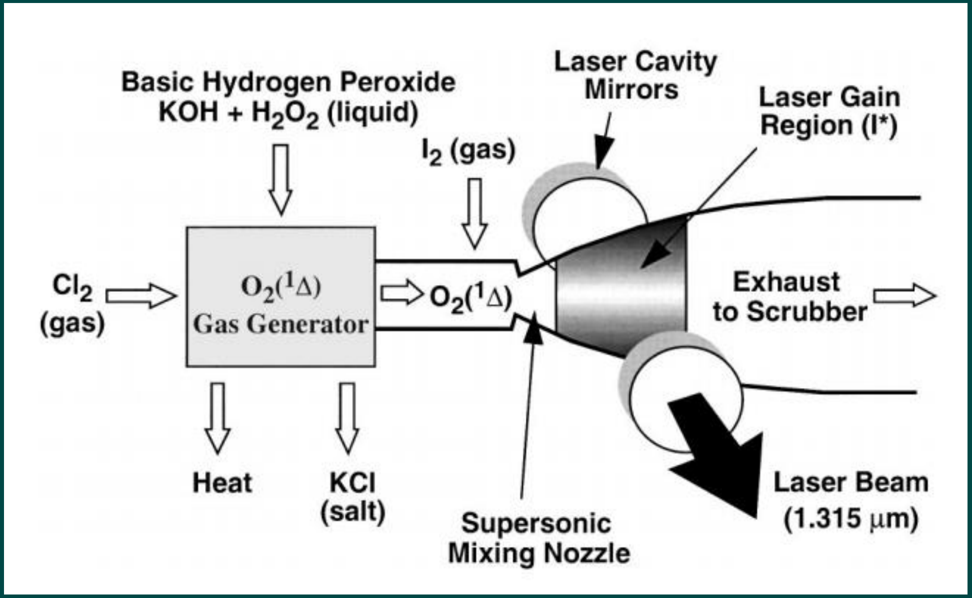


16 years of development and a cost of over $5 billion

Amy Butler (December 21, 2011). "Lights Out For The Airborne Laser". Aviation Week

Chemical oxygen iodine laser (COIL)

- The laser is fed with gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide.[12]
- The excited oxygen has a spontaneous lifetime of about 45 minutes.
- This allows the singlet delta oxygen to transfer its energy to the iodine molecules injected to the gas stream; they are nearly resonant with the singlet oxygen, so the energy transfer during the collision of the particles is rapid.
- The excited iodine then undergoes stimulated emission and lases at 1.315 µm in the optical resonator region of the laser



Challenging resonator conditions difficult to get a low M^2

Chemical oxygen iodine laser (COIL) limitations

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- The heart of the system was the COIL, comprising six interconnected modules, each as large as an SUV. Each module weighed about 6,500 pounds (3,000 kg).
- Each 747 could carry enough laser fuel for about 20 shots.
- To refuel the laser, YAL-1 would have to land.
- To maintain a safe (700 km) firing distance from the launch site, it would need a laser something like 20 to 30 times more powerful than the chemical laser currently in the plane.
- The adventure in this project is commendable, only the USA could have completed this, I am sure many useful technologies were understood.

Integrated Detection Systems

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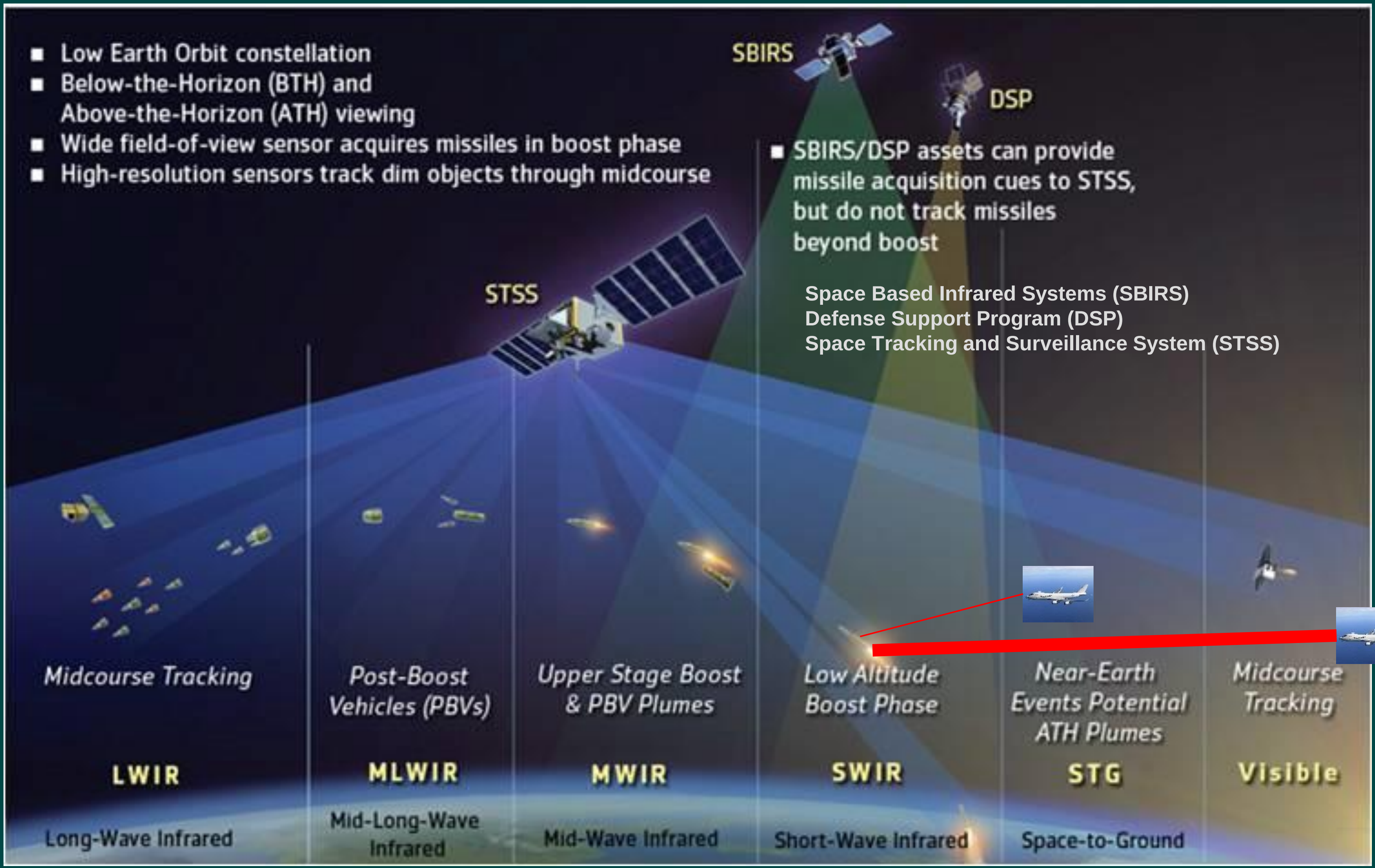

Rotatable beam delivery turret

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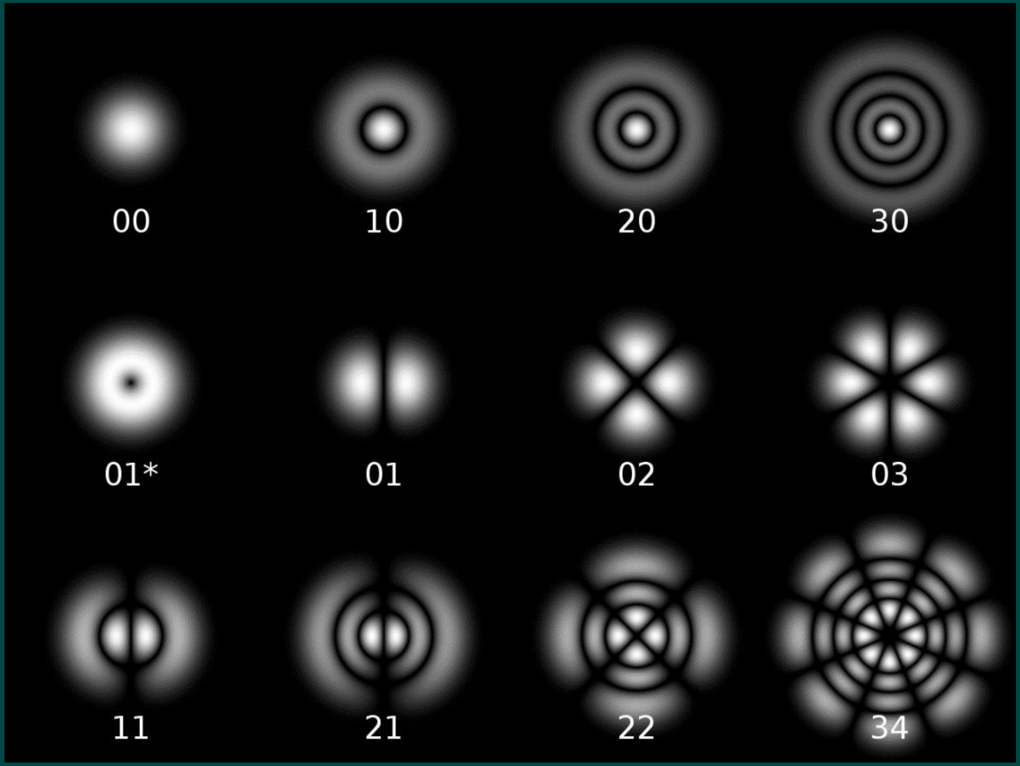
- The main laser, located in a turret on the aircraft nose, could be fired for 3 to 5 seconds, causing a missile to break up in flight near its launch area.

- To be effective the ALTB would have had to have been within a few hundred kilometers of the missile launch point.

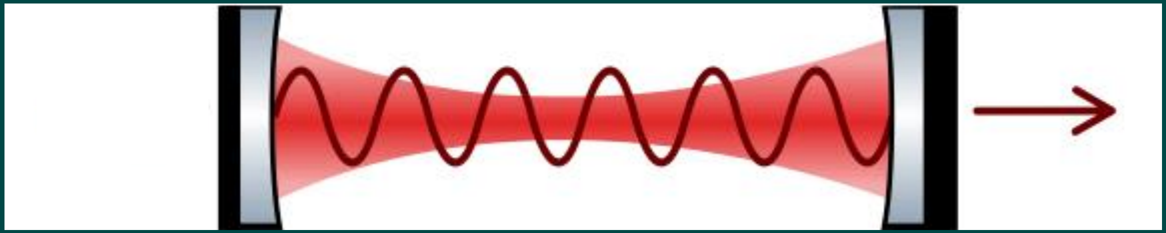
- On 12 February 2012, the YAL-1 flew its final flight, it was cancelled by defence secretary Robert Gates who said "to operationalise the system would require 10 to 20 747s, at a billion and a half dollars each, and a $100 million a year to operate."

Laser Transverse Modes – cylindrical symmetry



In a laser with cylindrical symmetry, the transverse mode patterns are described by a combination of a **Gaussian beam profile with a Laguerre polynomial.**

The modes are denoted TEM*pl* where *p* and *l* are integers labelling the radial and angular mode orders, respectively.



Laser Transverse Modes – rectangular symmetry

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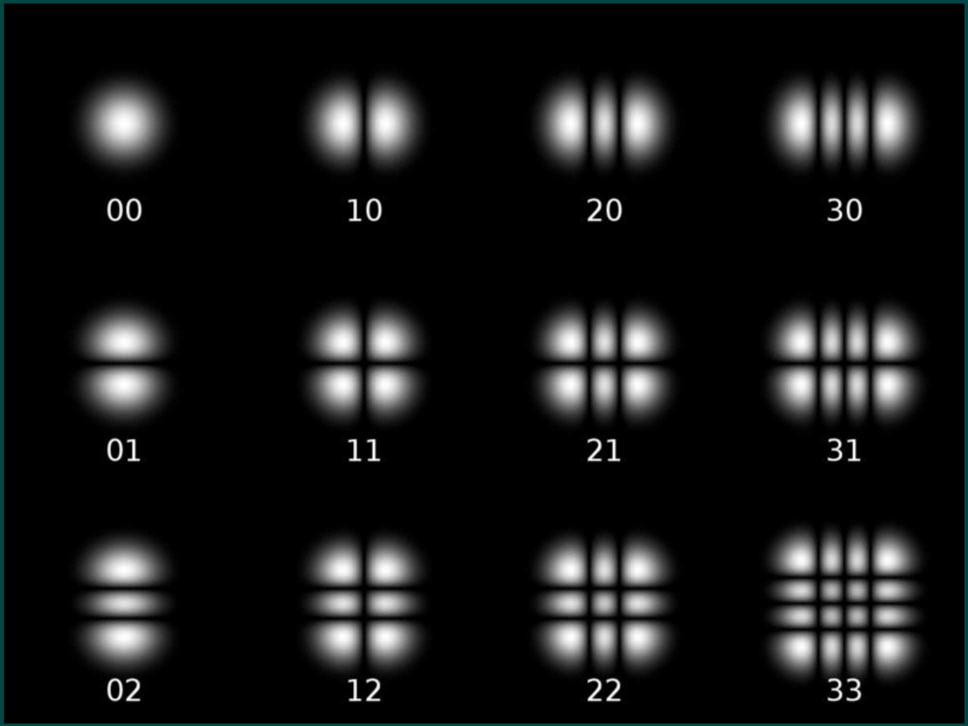
- In many lasers, the symmetry of the optical resonator is restricted by polarizing elements such as Brewster's angle windows. In these lasers, transverse modes with rectangular symmetry are formed.

- These modes are designated TEM*mn* with *m* and *n* being the horizontal and vertical orders of the pattern.



Transverse Modes in Fibres

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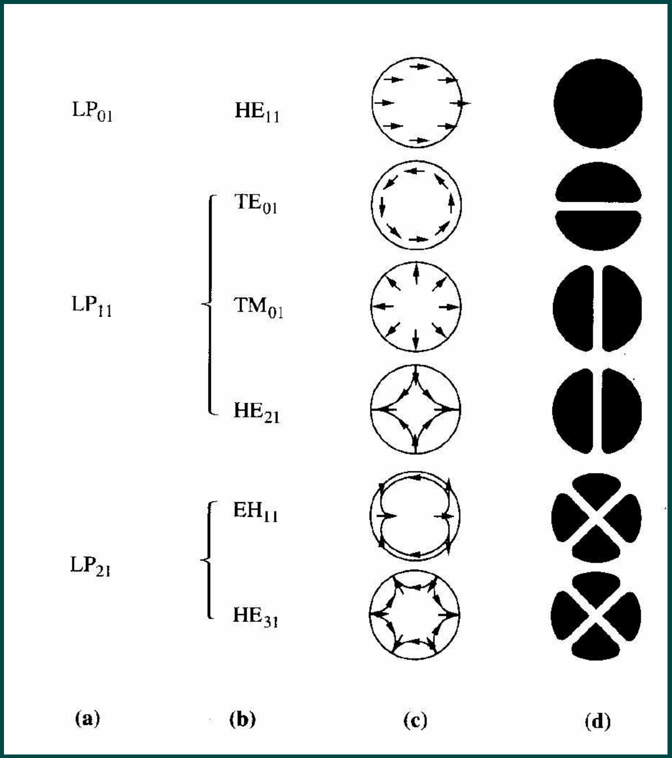
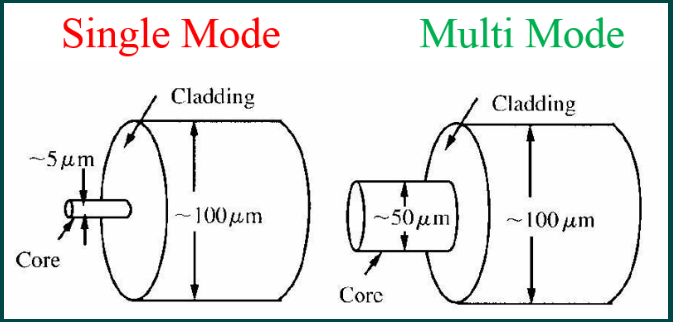
Some examples of low-order transverse modes of a step index fibre

(a) Linear polarized (LP) mode designations
(b) Exact mode designations
(c) Electric field distribution
(d) Intensity distribution of the electric field component





Angular Spread of Gaussian Beam

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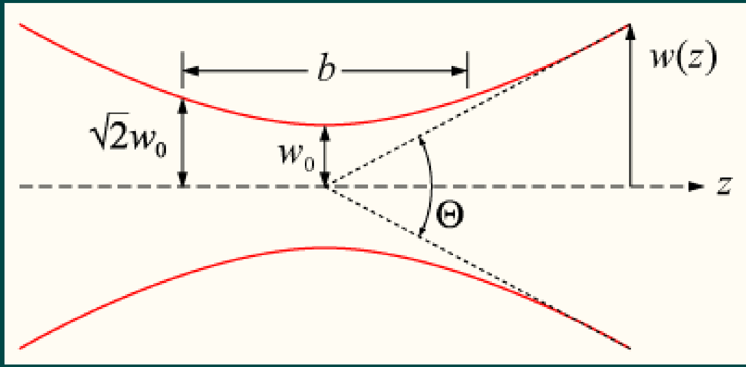
The parameter w (z) approaches a straight line for z >> z_0 . The angle between this straight line and the central axis of the beam is called the divergence of the beam. It is given by

$$\boldsymbol{\theta} \cong \frac{\boldsymbol{\lambda}}{\boldsymbol{\pi w_0}} \qquad (\theta \quad in\, radians)$$

The total angular spread of the beam far from the waist is then given by $\Theta = 2\theta$



z_0 = b/2 = Raleigh Range

Because of this property, a Gaussian laser beam that is focused to a small spot spreads out rapidly as it propagates away from that spot. To keep a laser beam very well collimated, it must have a large diameter.

M^2 Factor – Beam Quality Factor

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- The M^2 factor, also called *beam quality factor* or *beam propagation factor*, is a common measure for the beam quality of a laser beam.
- The beam divergence is: $\theta = M^2 \lambda/\pi\omega_0$, in my opinion this was the problem for the COIL system
- where w_0 is the beam radius at the beam waist and λ the wavelength. A laser beam is often said to be "M^2 times diffraction-limited". A diffraction-limited beam has an M^2 of 1, and is a Gaussian beam. Smaller values of M^2 are physically not possible.

M^2 Factor – Beam Quality Factor

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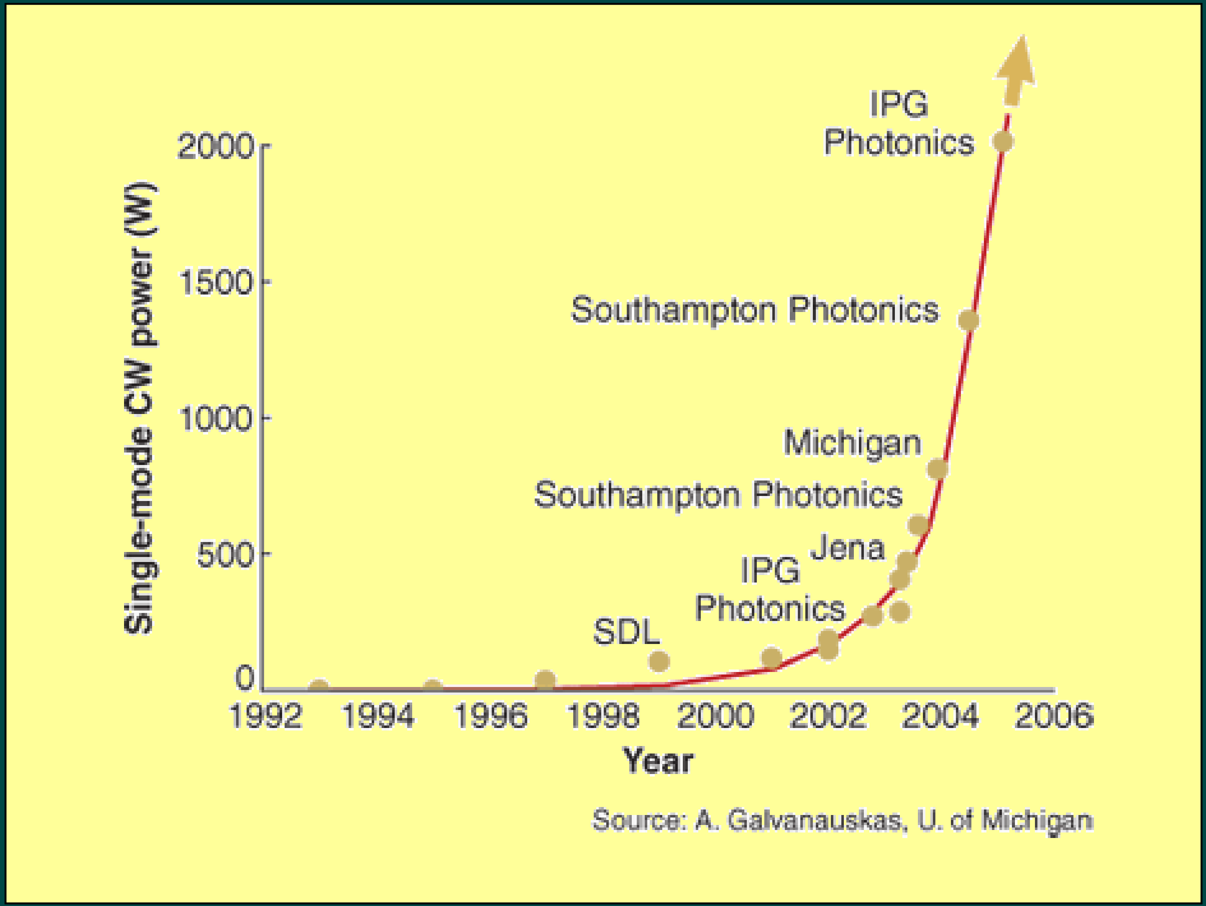
- The M^2 factor of a laser beam limits the degree to which the beam can be focused for a given beam divergence angle, which is often limited by the numerical aperture of the focusing lens.

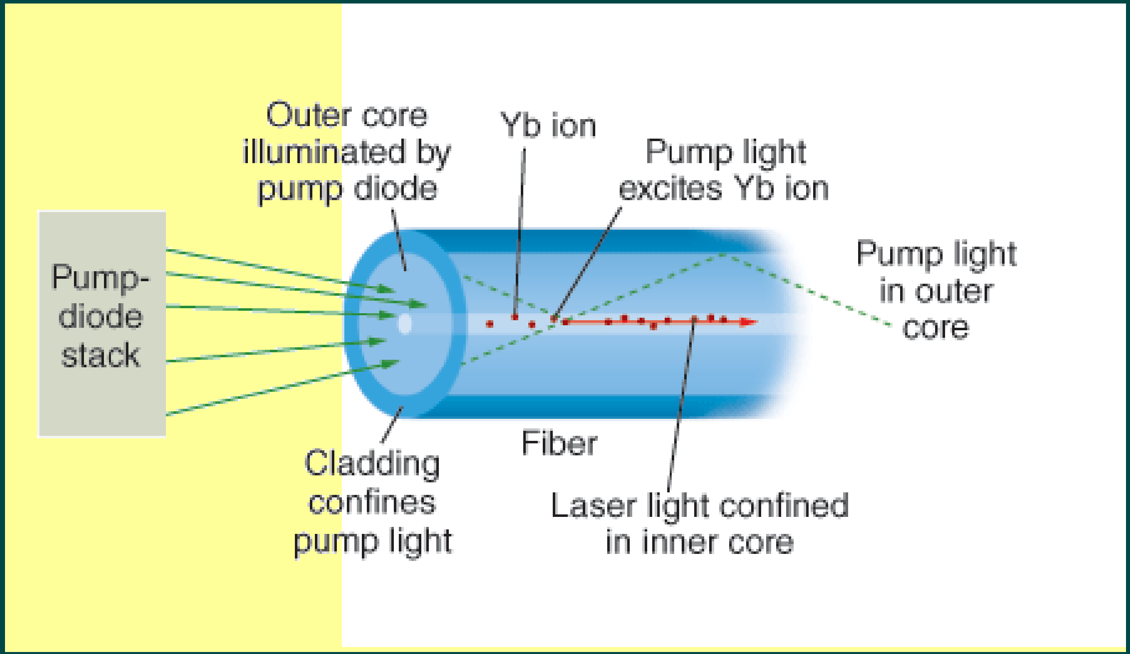
- Together the optical power & the beam quality factor determine the brightness (more precisely, the radiance) of a laser beam.

High Power Fibre Lasers



The steady march of high-power single-mode output from ytterbium-doped fibre lasers is continuing.

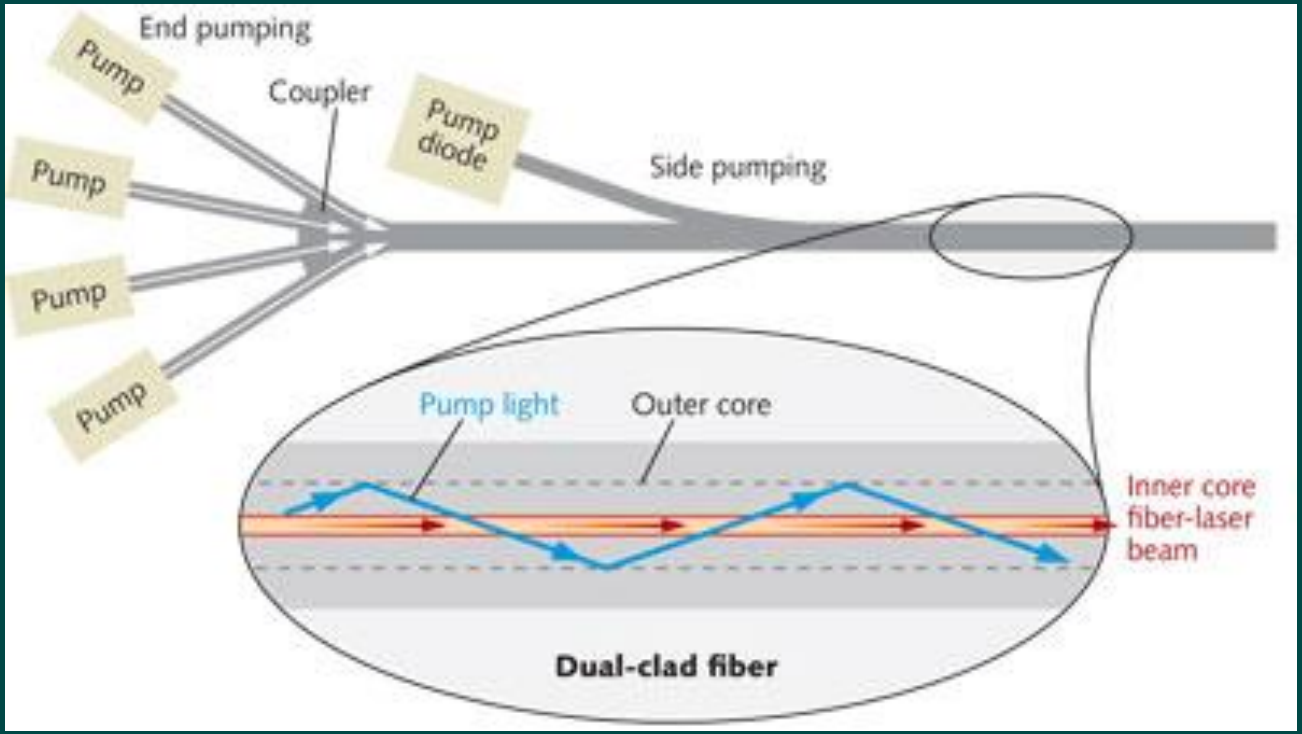
Fibre Laser Operation



Pump light from a diode-laser stack illuminates the outer core of a dual-core fiber (focusing optics are not shown for simplicity).
The cladding confines the pump light in the outer core so it passes through the inner core.
One pump photon excites an ytterbium atom in the inner core,
which emits light that is confined in the inner core,
becoming part of the fiber-laser beam

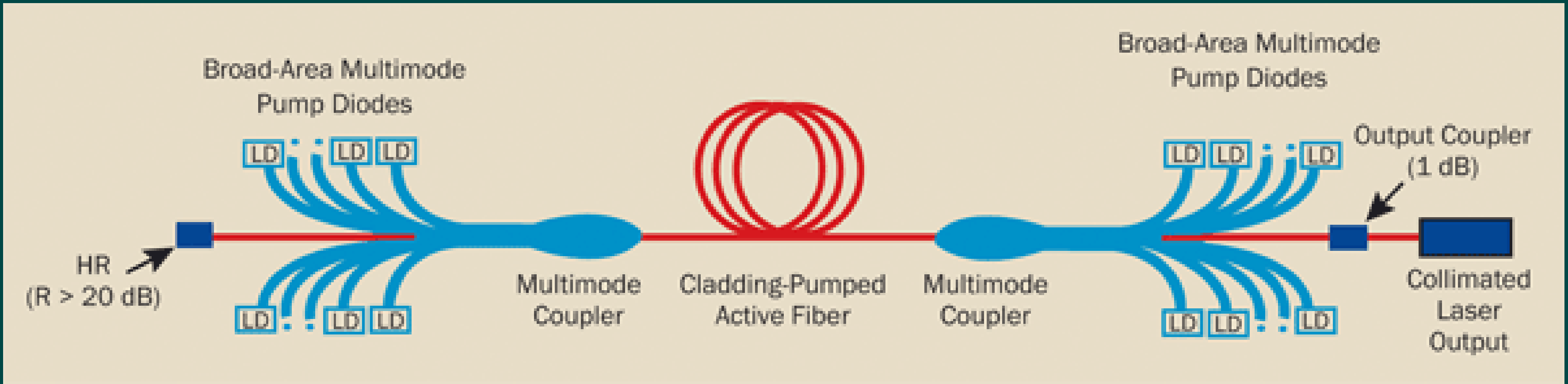
IPG Photonics approach

- A fiber laser can be end-pumped with one or many lasers, or side-pumped (usually with many lasers) by side-coupling pump light into the outer core.



A typical single-mode fibre laser utilizing single-emitter diodes

- The emission wavelength is a function of choices in the doped fibre and the type of reflector - a typical example would be Bragg gratings.
- This single-mode core is typically 5 to 12 µm in diameter. The double-clad fibre consists of an inner single-mode core doped with the appropriate rare-earth ions such as: neodymium, erbium, ytterbium and thulium.



Fibre lasers are available up to 50 kW in power from IPG Photonics

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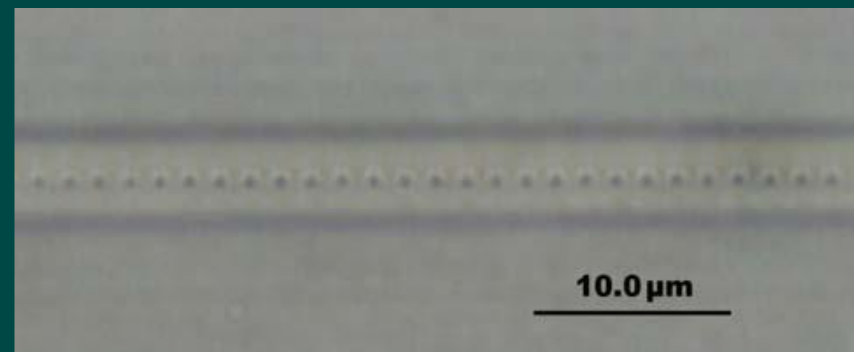
http://www.youtube.com/watch?v=LVpD5y7ngA4



Optical microscope image of the core of a Ytterbium doped fibrelaser showing the individually inscribed grating periods of a grating for operation at 1064 nm.

Courtesy: Graham D. Marshall et al

Single mode operation is vital

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- The highest single-mode power available from a fiber laser is 10 kW, from IPG Photonics, single mode M^2 ~1
- Hence near diffraction limited performance
- The IPG system, has a master oscillator that produces a kilowatt of optical power that is fed into an amplifier stage pumped at 1018 nm with light from other fibre lasers.
- IPG single mode fibre lasers have a Mode Field Diameter of ~15 µm
- Due to the high efficiency of these lasers ~ 30%, these lasers have modest water cooling requirements
- The entire laser system is about the size of two refrigerators.

IPG Photonics Lasers

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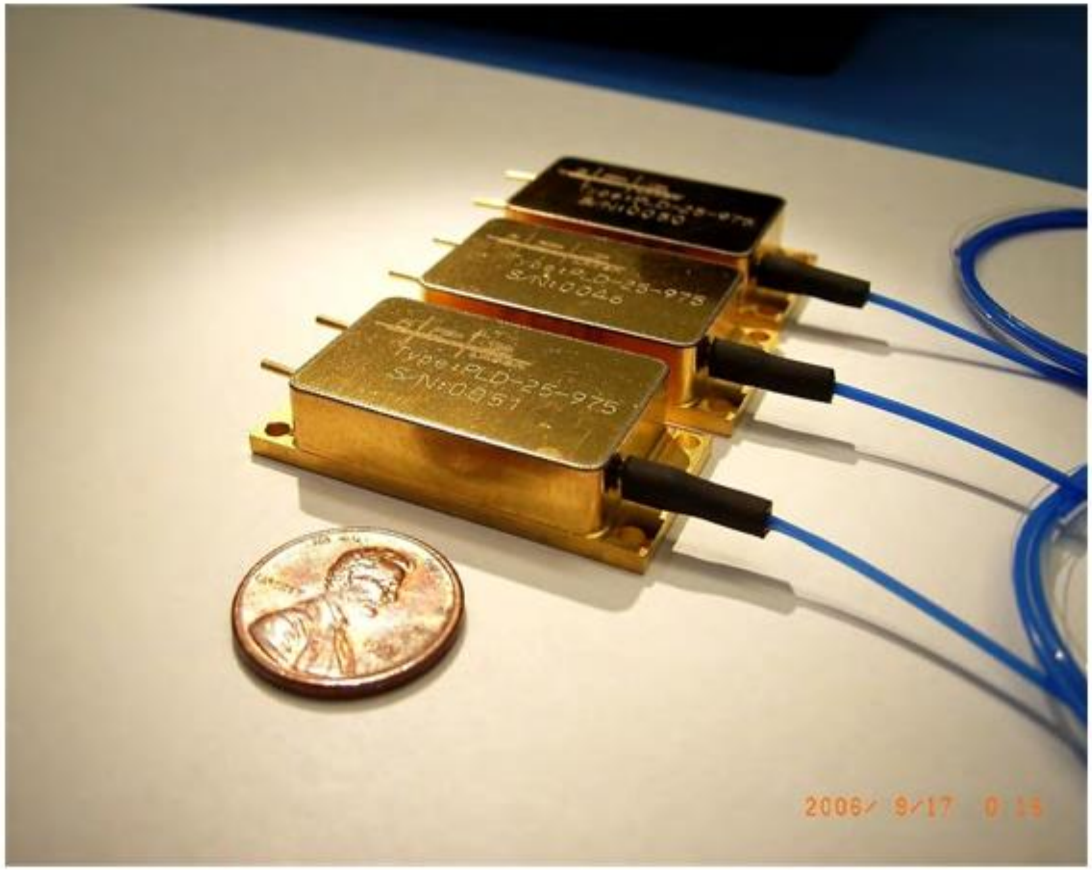
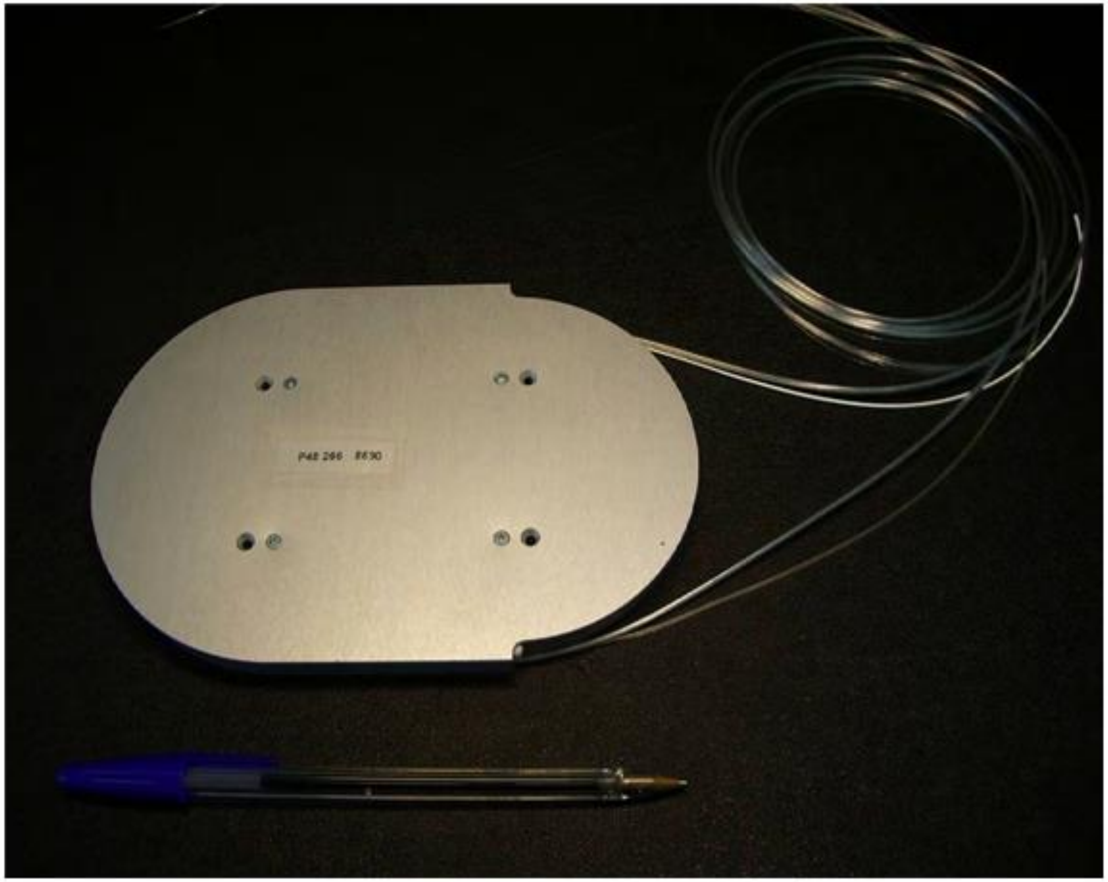
- The highest multimode power reached is 50 kW, also by IPG Photonics.
- The system relies on incoherent beam combination, so it's not a super high-quality beam (beam parameter product of 10, M^2 of 33).
- Lasers with large values of M^2 have limited effective range due to the large diffraction spreading angle: $\theta = M^2 \lambda/\pi\omega_0$

25W Pump Diode Modules - IPG

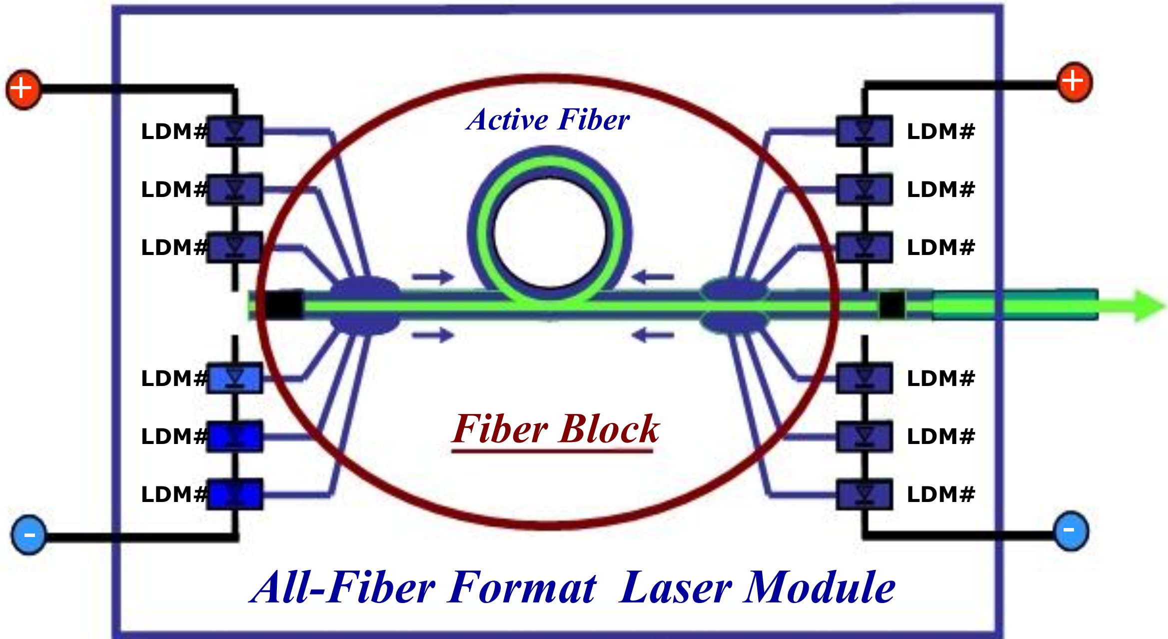


https://www.youtube.com/watch?v=ofEqFlqkiS0 fibre laser operation

400W...700 W Ytterbium Fiber Blocks - IPG



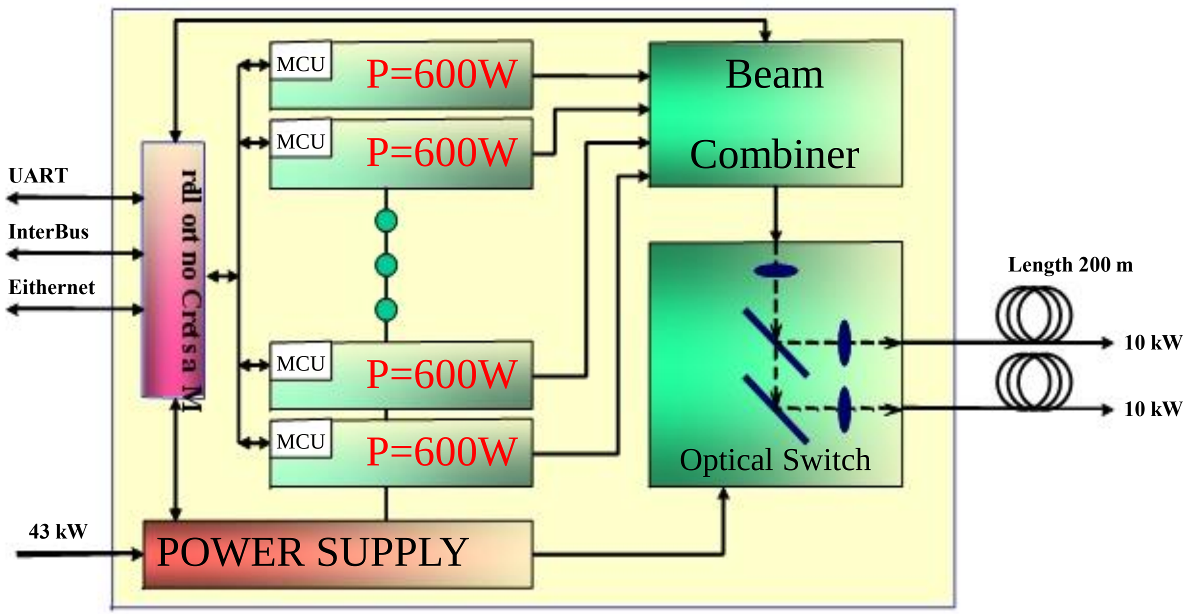
IPG Conception - IPG



- Compact integrated optical design
- In parallel combining by single emitter diodes
- Side pumping
- Robust mechanical construction

kW-(multimode)-Fiber Lasers - IPG

YLR-10000: Block Diagram

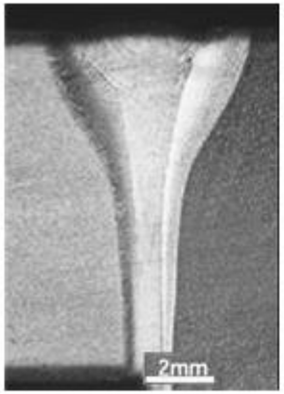


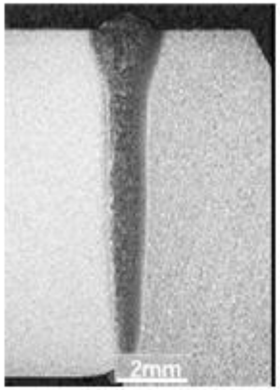
Welding of Gear Box Parts

CO_2-Laser ***Electron beam*** ***Fiber Laser***

Fraunhofer IWS Institut Werkstoff- und Strahltechnik







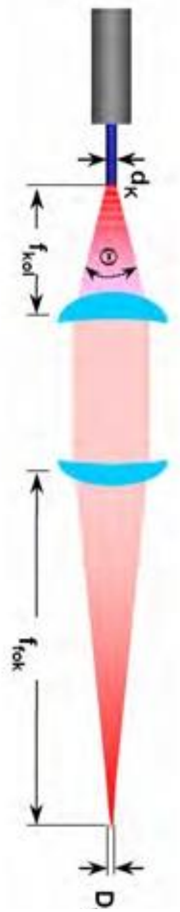
-Low heat input; Low distortion

-Reduced crack risk

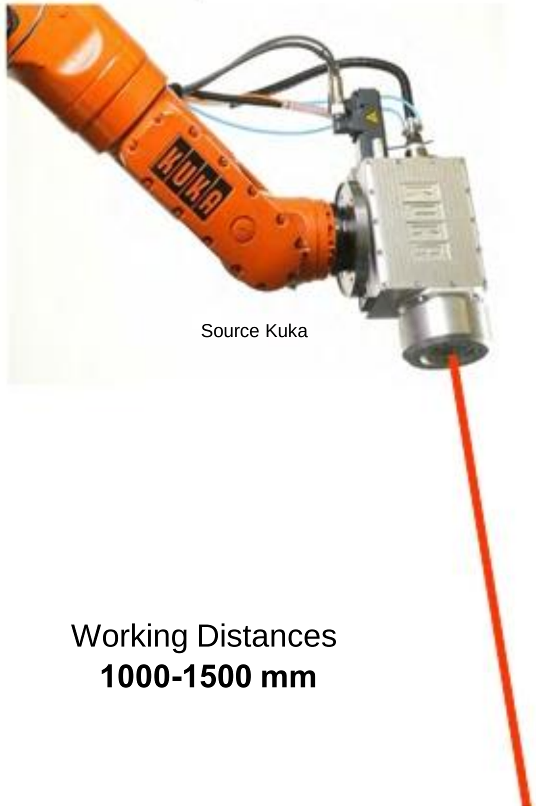
YLR4000-S

http://www.youtube.com/watch?NR=1&v=8B35zeYmeO4&feature=endscreen **fibre laser cutting**

Fiber Laser Remote Welding - IPG

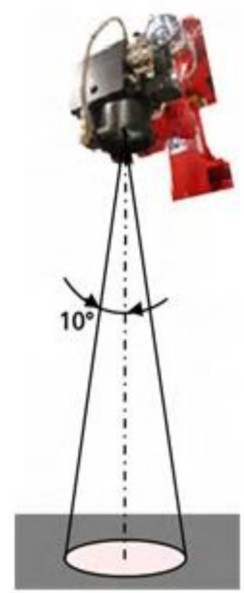


Scannerfree Remote Processing



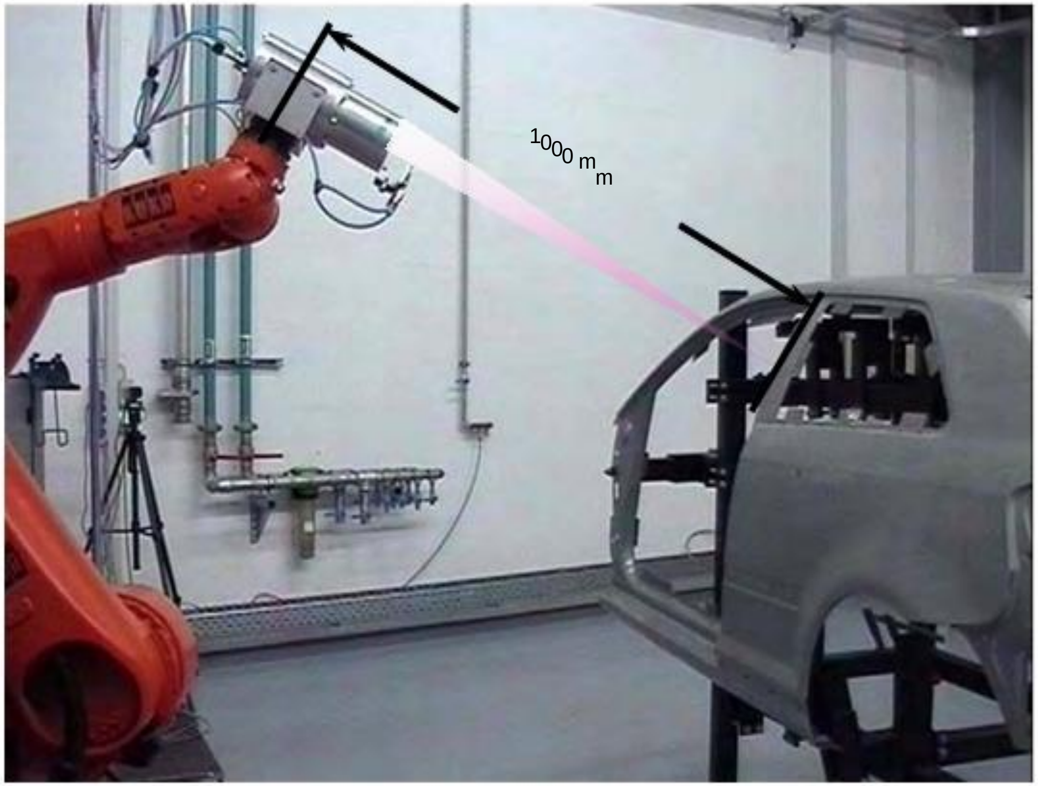
Working Distances
1000-1500 mm

Scanner Remote Processing



Working Distances
~ 500 mm

Remote Welding of Body in White (BIW)



High productive stitch welding for body in white

Fibre lasers replacing CO_2 lasers

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Fanuc welding robot using fibre laser – 50kW lasers are available

US Navy Laser Weapon System (LaWS) - NRL

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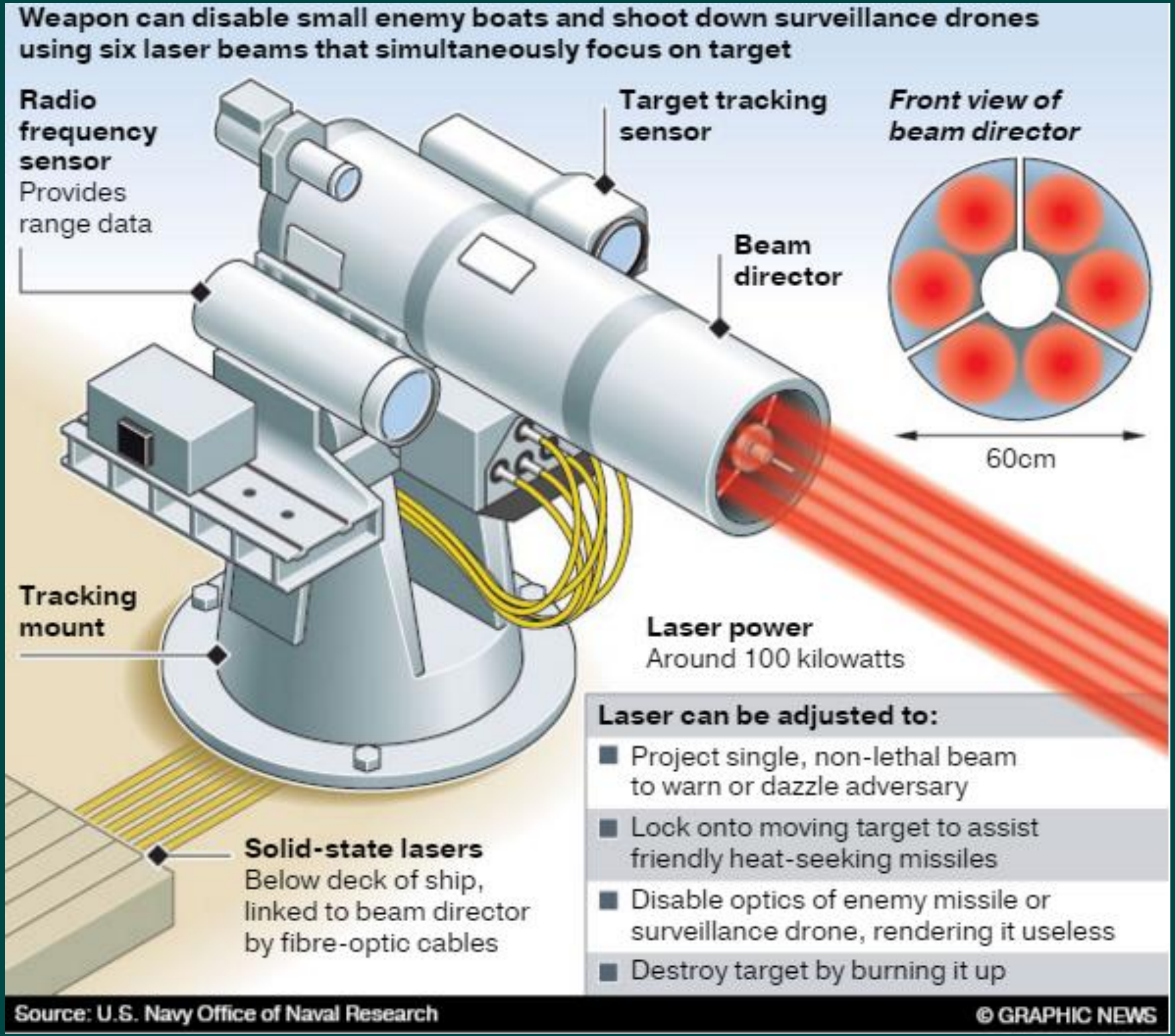
- The US Navy's Laser Weapon System (LaWS) contains six individual fiber lasers with their beams incoherently combined into a single 33 kW output. (*Courtesy of US Navy*)

http://www.laserfocusworld.com/articles/print/volume-48/issue-04/features/the-state-of-the-art.html

US Navy Laser Weapon System (LaWS)



US Navy Laser Weapon System (LaWS)

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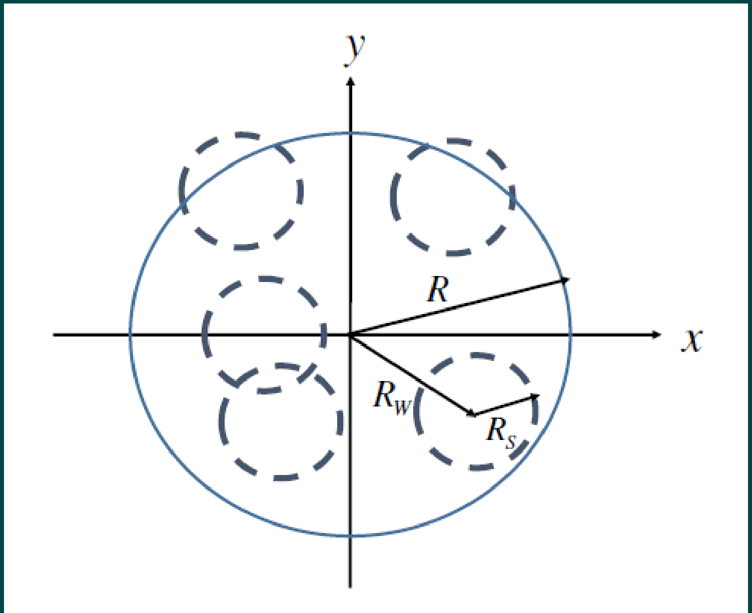
Difficulties

- Absorption/scattering
  1. *Molecules, Atoms and Aerosols scatter the beam. This can be minimised by operating at a wavelength of $1.045 \mu m$*
  2. *At high powers heating of the medium causes thermal blooming*
- Thermal blooming
  1. *The absorbed energy locally heats the air and leads to a decrease in the air density which modifies the refractive index*
  2. *Thermal blooming can be mitigated by path clearing, which can be achieved by vapourising the aerosol*

Turbulence Challenge

- Turbulence leads to spreading of the laser beam spot size Rs and wandering of the laser beam centroid Rw. The Figure[2] shows the laser beam spot (dotted circles) at several instants in time.
- Adaptive optics can compensate for turbulence but not diffraction or poor beam quality.
- R_W is the centroid displacement (wander), and R_S is the increase in spot size (spreading)
- $R = (R_w^2 + R_S^2)^{1/2}$



Diffraction

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- Limit diffractive spreading over the range
- The individual spot sizes (radius) of the beams must be large enough at the source and have good optical quality. Ro ≥ 10 cm

Incoherent beam combining

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- Coherent combining would require a narrow spectral linewidth, phase locking, as well as polarisation alignment of all the lasers.
- These are very difficult requirements for high power lasers and in the presence of moderate turbulence the benefits of coherent combining are lost.
- Incoherent combining is much more practical
- Its range can be extended using adaptive optics

Incoherently combined fiber lasers individually directed to the target.

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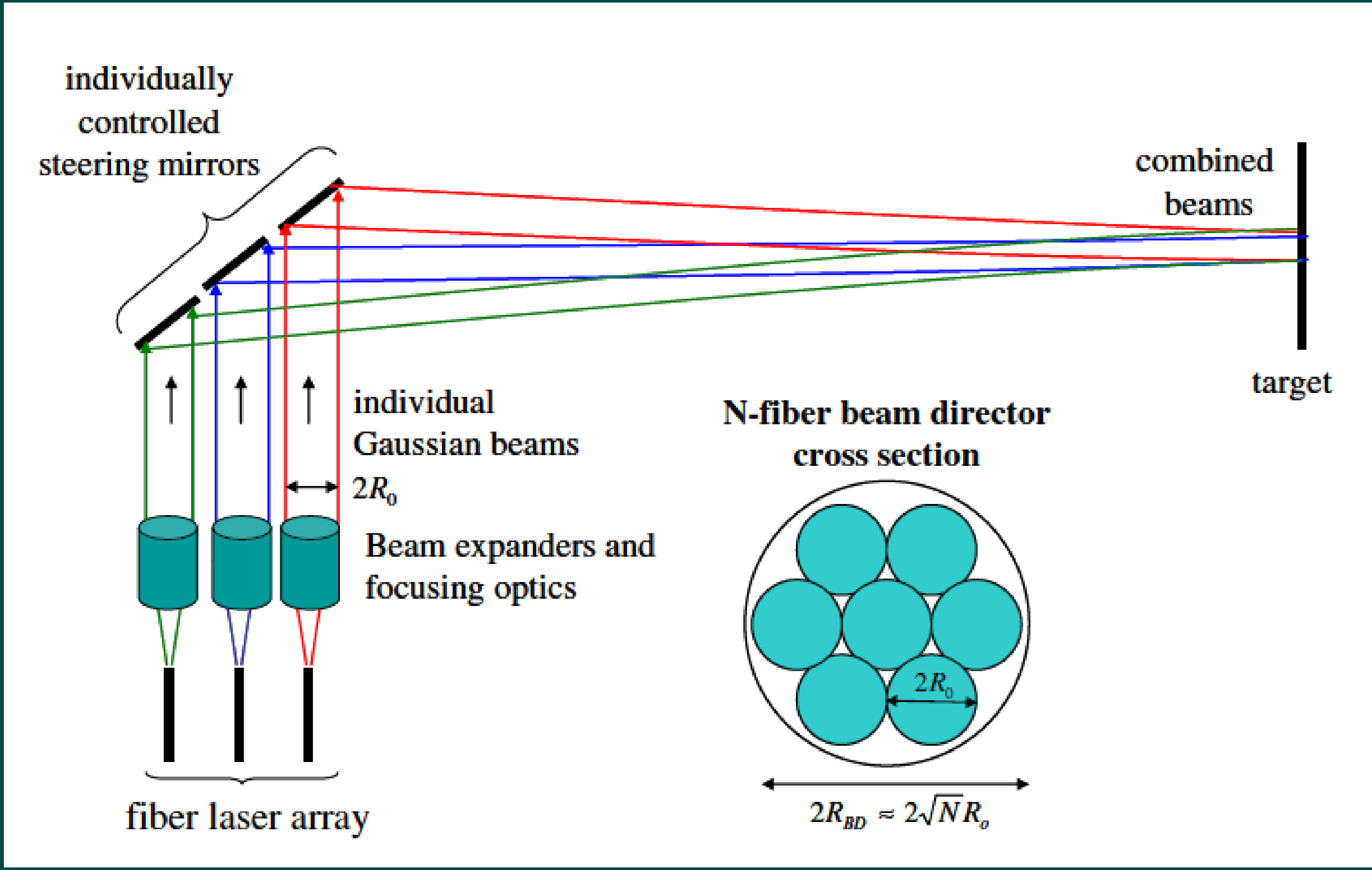

Sprangle et al NRL,[2]

NRL beam director used for incoherent combining

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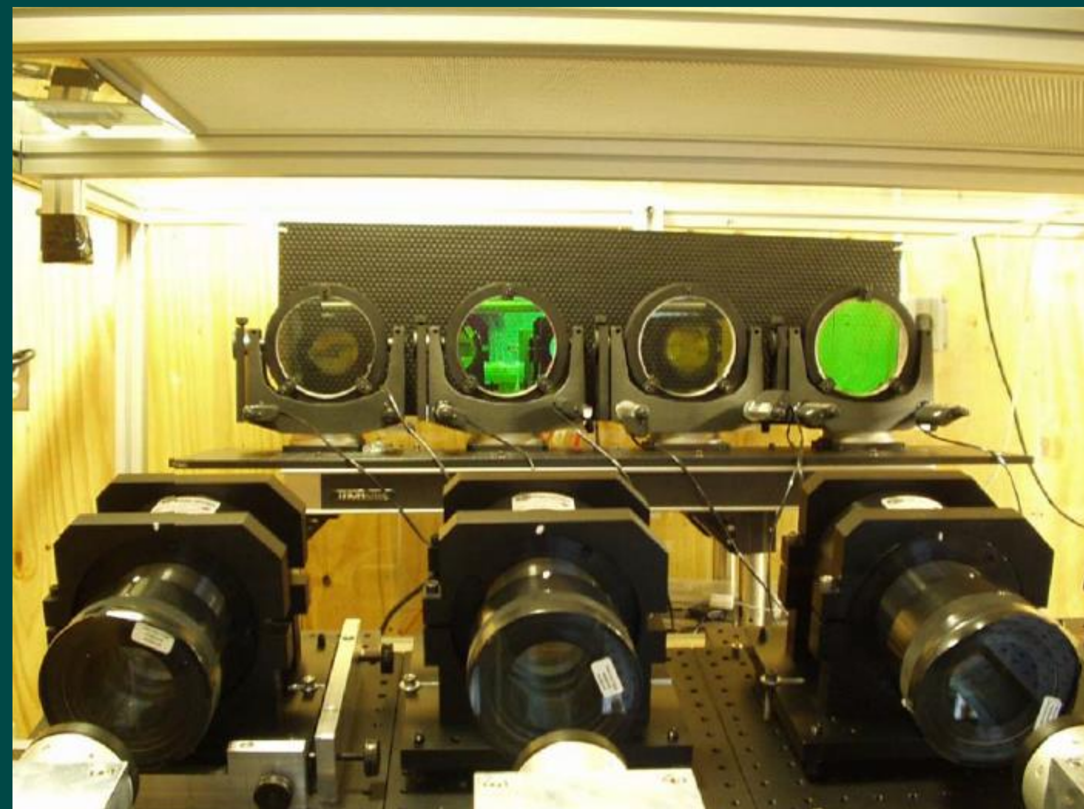
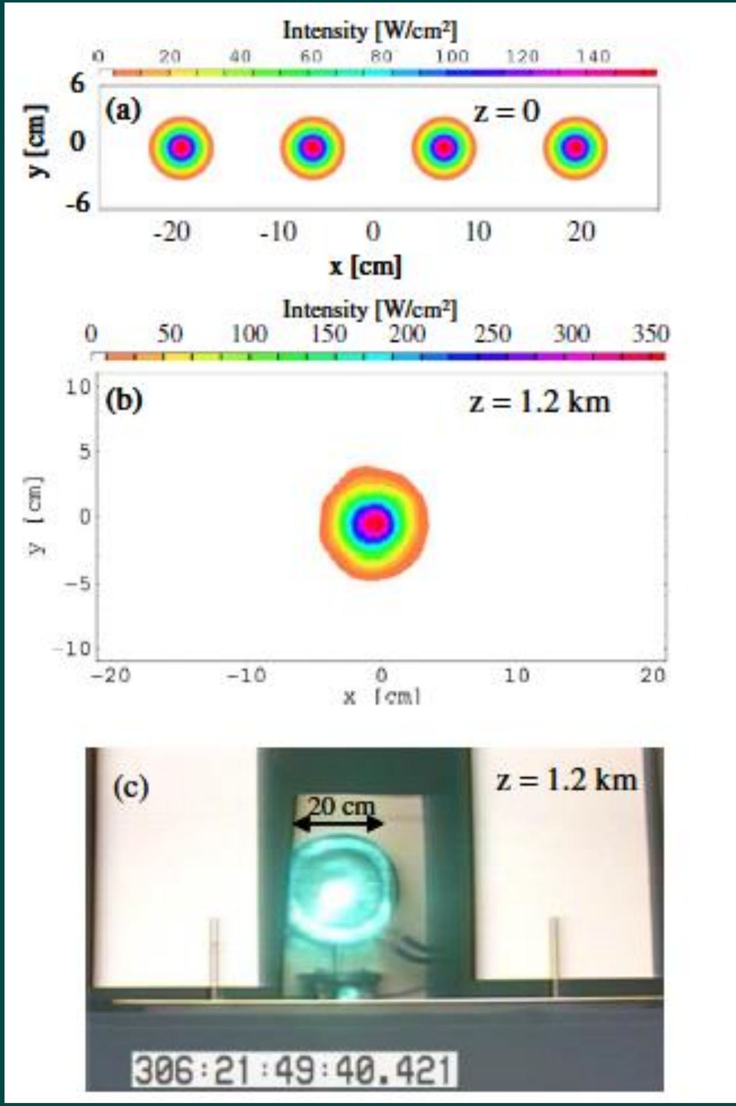
- Three of four fiber laser collimators and beam expanders are shown in the foreground.[2]

- Four individually controlled steering mirrors are shown in the background.



Incoherent beam combining

- Simulation showing a 2 s time-averaged transverse intensity profile of laser beams at [2]
- (a) the source and
- (b) incoherently combined on a target at a range of 1.2 km for a turbulence strength of C_n^2 = 5 × 10−14 $m^{-2/3}$, wind speed of 2.5 m/s, aerosol scattering coefficient of 0.05 km^{-1}, and mechanical jitter of 1–2 μm. The individual initial spot size is ~2.5 cm and the combined spot size on target is ~3–4 cm.
- (c) CCD camera image of four beams incoherently combined on target (20 cm diameter power meter) at a range of 1.2 km. The total transmitted power was 3 kW and the propagation efficiency ~90% in the experiment.



US Naval Defense - NRL

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Success in targeting drones

https://www.youtube.com/watch?v=D0DbgNju2wE

Lockheed Martin 30 kW system using Spectral beam combining

Lockheed Martin sets new record with a single 58-kW beam.

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- Lockheed Martin will deliver a new 60-kW weapon to the US Army With all phases from demonstration to development completed, Lockheed will ship the combined fiber laser to the US Army Space and Missile Defense Command/Army Forces Strategic Command in Huntsville, Alabama.
- 19th March 2017 – David Szondy

The present laser is close to the diffraction limit. That is, it's close to the physical limit for focusing a laser on a single spot without interfering with itself, but it's still highly efficient – translating over 43 percent of the electricity fed into it into laser light

Lockheed Martin 30 kW

BETHESDA, Md., March 3, 2015 – Lockheed Martin’s [NYSE: LMT] 30-kW fiber laser system successfully disabled the engine of a small truck during a recent field test, demonstrating the rapidly evolving precision capability to protect military forces and critical infrastructure.
http://www.sme.org/MEMagazine/Article.aspx?id=84571&taxid=3440#sthash.gn1DnEoL.dpuf

Spectral Beam Combining

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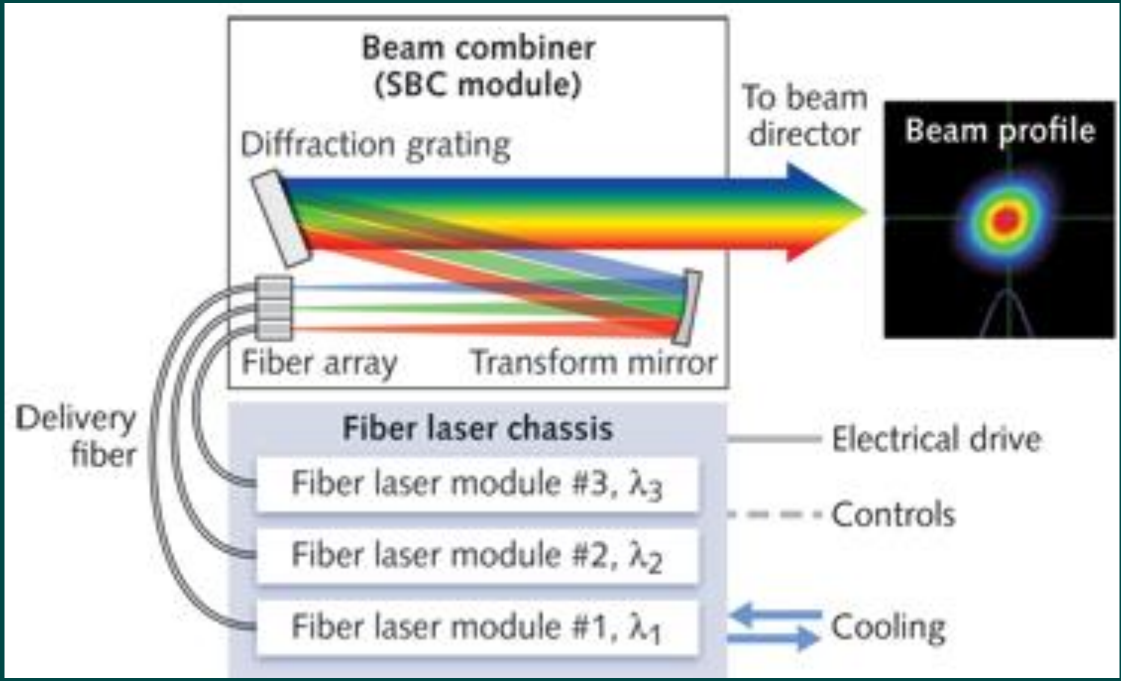
- The unique process, called Spectral Beam Combining, sends beams from multiple fibre laser modules, each with a unique wavelength, into a combiner that forms a single, powerful, high quality beam.



Lockheed Martin demonstrate 30kW Laser

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- The 30-kilowatt beam combines many fibre lasers operating a slightly different wavelengths into a single "near perfect" band of light.
- Lockheed says the upgraded system produced the highest power ever documented while still retaining beam quality and electrical efficiency and using 50% less electrical power than solid-state lasers.

Lockheed sees the new lasers as eventually leading to new systems to provide protection against swarms of: drones, rockets, and mortars that would overwhelm conventional defenses.

Prototype Defensive UK 50kW Laser Weapon by 2019

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The UK Ministry of Defence has officially awarded a £30m contract to produce a prototype laser weapon, known as Dragonfire. UK Defence Journal – January 5th 2017 – George Allison

The contract was awarded to 'UK Dragonfire' a consortium comprising the companies MBDA, Qinetiq, Leonardo-Finmeccanica GKN, Arke, BAE Systems and Marshall ADG UK.

HELLADS or "High Energy Liquid Laser Area Defense System."

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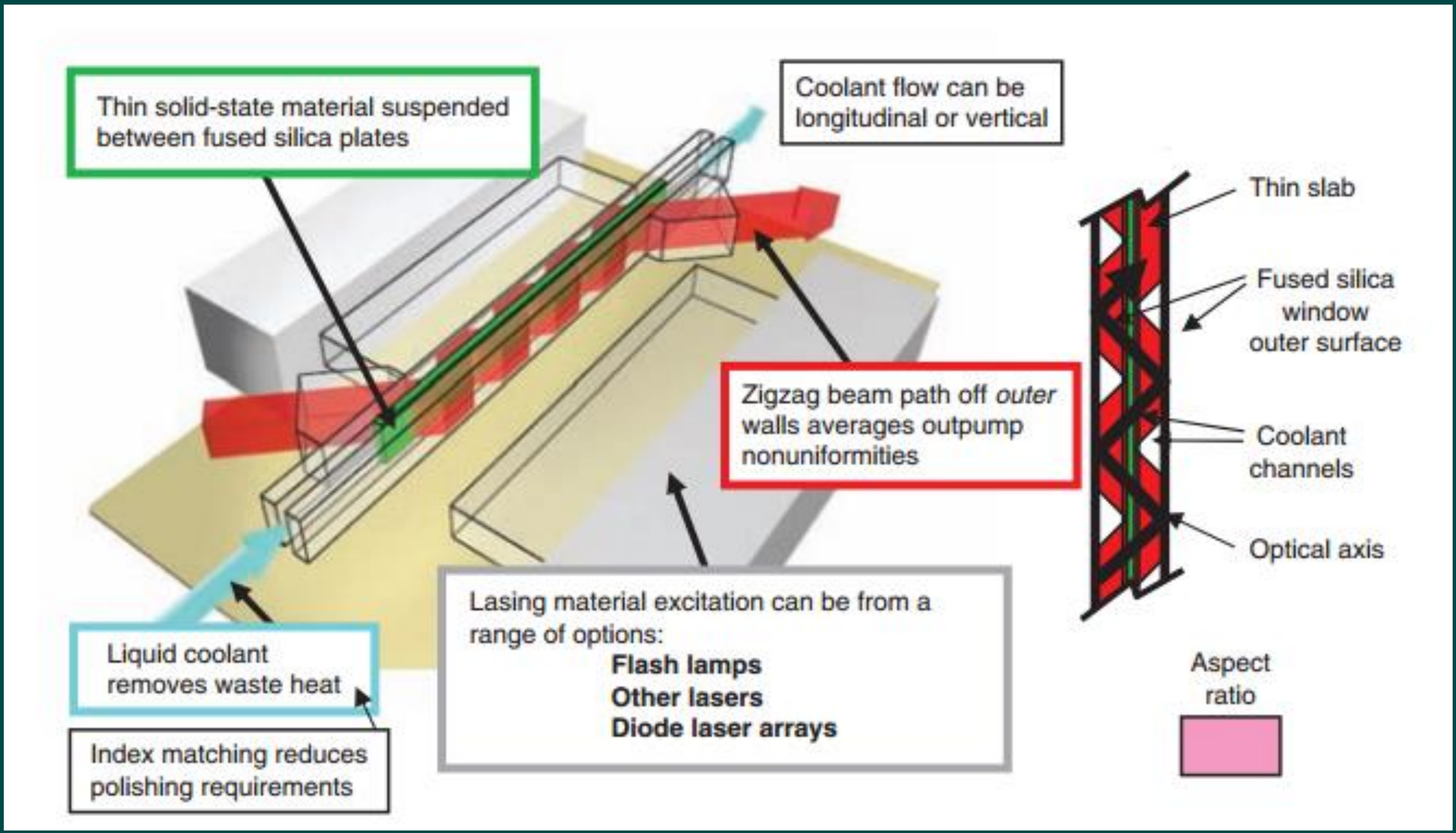
- Weaponeer Textron will get $21 million in Darpa bucks "to design, fabricate and test a Unit Cell Module for a 150 kilowatt (kW) Laser Weapon System," according to a company press release.
- The end product will be the size of a large refrigerator with a weight of 1650 pounds.

Textron say that their HELLADS design is based on "proprietary ThinZag Ceramic solid-state laser technology"

Nd:YAG Ceramic ThinZag® High-Power Laser



Source: High-Power Laser Handbook – Daniel E Klimek

Advances in Technoogy

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- There has also been a revolutionary development in laser gain material.
- Cubic structure materials like YAG can now be fabricated as ceramics with optical uniformity that is better than found in YAG crystals (for both dopant uniformity and variations in index of refraction), with scattering loss coefficients comparable to YAG crystals
- These materials can also be produced in sizes that YAG crystals cannot achieve (e.g., 400 × 400 mm^2 slabs)

Six TZ-3 modules for 100-kW ThinZag on two coupled optical tables

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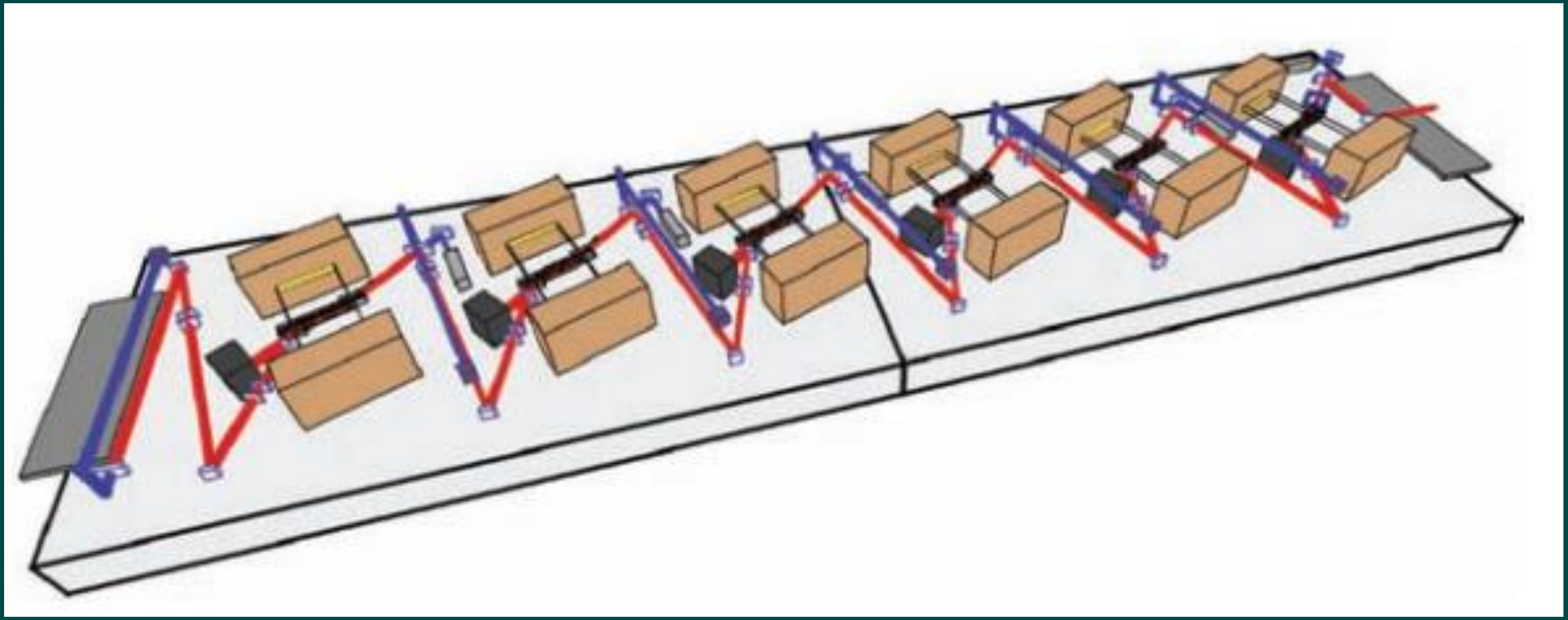

Conclusions

- The Boeing YAL-1 Airborne Laser demonstrated that laser weapons are better used for short range defence applications
- This can be confirmed using the beam divergence equation: $\theta = M^2 \lambda / \pi \omega_0$
- The US Navy LaWS system and the Lockheed Martin fibre laser systems have shown that High Power Lasers are useful for defence over a range of 10 to 15 km
- Such systems can be used for defence against weapons such as: Drones, Missiles, Rockets, Mortars, Shells etc

Conclusions

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- The current short range fibre laser based systems are increasingly effective and realistic.
- The HELLADS or "High Energy Liquid Laser Area Defense System.“ is showing increasing promise and offers greater than twice the power of the fibre based systems – 150 kW
- Laser beam effectiveness is all about high watts/m^2 and beam quality on the target

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